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Characterization and simulation of the effect of punching on the high cycle fatigue strength of thin electric steel sheets

Helmi Dehmani [a,b,c*], Charles Brugger [b], Thierry Palin-Luc [b], Charles Mareau [c], Samuel Koechlin [a]

[a] *Emerson-Leroy Somer, Boulevard Marcellin Leroy, Angoulême, France*
[b] *Arts et Métiers ParisTech, I2M, CNRS, Esplanade des Arts et Métiers, Talence, France*
[c] *Arts et Métiers ParisTech, LAMPA, Boulevard du Ronceray, Angers, France*

Abstract

Rotors of electric machines are built from stacks of thin steel sheets. The fabrication process of these components usually involves punching operations that generate defects on the steel sheet edges. In this study, high cycle fatigue tests are performed on punched and polished edges specimens to investigate the effect of the punching process on the fatigue behaviour of these thin sheets. Results show a significant decrease of the fatigue strength for punched specimens. SEM observations of fracture surfaces reveal that crack initiation always occurs on a punching defect. Residual stresses on punched edges are analysed using X-Ray diffraction techniques. High tensile residual stresses along the loading direction are found. Some specimens edges were scanned using 3D topography prior to the fatigue tests. This allows for identifying the real geometry of the most critical defect. Murakami criterion was then evaluated in order to take into account the effect of defects. The best trend of the experimental results is given when residual stresses are taken into account. Local elastic stresses for 3 defects geometries have been calculated using FEA. Crossland fatigue criterion has been evaluated to try accounting for the local stress state around defects. Results show that the assessed fatigue strength is overestimated using this criterion.

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Keywords: Thin sheet, electrical steel, punching, defects, crack initiation, high cycle fatigue

* Corresponding author. Tel.: +33-556845333; fax: +33556845366.
E-mail address: helmi.dehmani@ensam.eu

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1. Introduction

Electrical steels are increasingly used for building high-speed motors, hybrid and electric traction machines. Because of their better magnetic properties, new generations of Fe-Si thin sheets are used in rotors to improve energy efficiency. The reduction of the iron losses is mainly achieved by decreasing the thickness below 0.5 mm, increasing the grain size, and adjusting the chemical composition (mainly the silicon content). Because it offers an important production rate, punching process is used to obtain electric motor components. However, it generates a specific morphology on the cut edge of components. Four different zones are usually observed: roll-over, shear zone, fracture zone, and burr [1, 2]. Defects with different sizes are observed on the edge. In addition to the geometrical defects, this process also generates hardening and residual stresses locally on the edge [3, 4, 5]. In operation, rotor components are subjected to a cyclic loading. The load cycle is defined as the start and stop of the electric machine. Designers should consider the effect of the punching process on the high cycle fatigue behaviour of these thin sheets to avoid in service failure of components [6]. The main objective of this work is to study the effect of punching process on the high cycle fatigue resistance to crack initiation for thin sheets. The geometrical defects, hardening and residual stresses induced on the edge by this process are investigated.

2. Material and testing conditions

The studied material is a non-oriented fully-processed sheet of iron silicon alloy delivered as rolled sheets with 350 µm nominal thickness. Its chemical composition is given in Table 1.

Table 1 : Chemical composition of the studied Fe-Si alloy

Chemical composition	Si	Mn	Al	Fe
Mass (%)	2-3.5	0.2-0.6	0.4-1.2	95-98

Metallographic observations in Figure 1-a reveal an equiaxed microstructure with a mean grain size of about 100 µm. EBSD analyses show a slight rolling texture induced by the rolling process though the macroscopic mechanical properties are quasi-isotropic. The material has a yield strength σ_y of about 400 MPa and a maximum tensile strength, Rm, of about 500 MPa. The Young's modulus is about 180 GPa and the Poisson's ratio ν is 0.3.

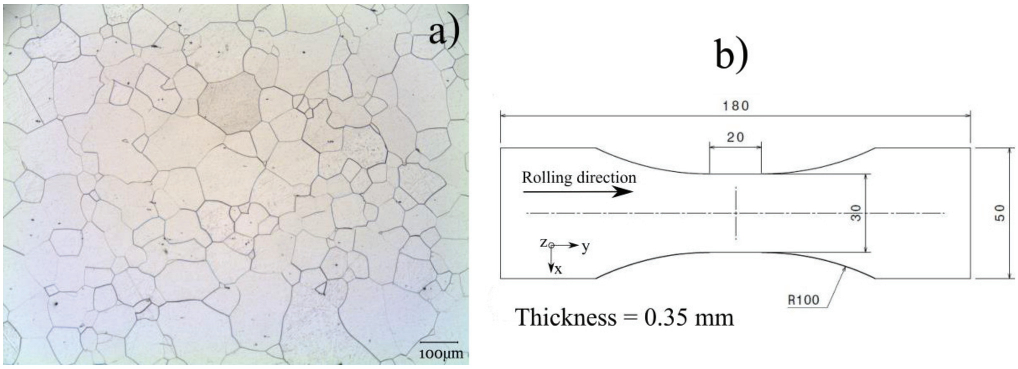

Figure 1 : (a) Microstructure of the studied Fe Si rolled sheets after Nital etching (b) Geometry of the specimens used for fatigue tests

Smooth specimens have been used for the fatigue tests. They were punched out from sheets with the same punching conditions than those used for producing real components, their longitudinal axis being parallel to the rolling direction. The specimen geometry is represented in Figure 1-b.

To evaluate the impact of punching on fatigue properties, some fatigue tests were also performed on specimens with polished edges. Polishing was expected to remove geometrical defects, to reduce the plastically strained region and to attenuate residual stresses due to punching. Polishing operations were carried out using P1200 then P4000 silicon carbide papers until removing all visible defects. High cycle fatigue tests were performed in air under uniaxial tension loading and load control at a loading frequency of 65 Hz using a resonant fatigue testing machine (Vibrophore type). Tests were carried out on both punched and polished specimens at room temperature (≃20°C) with a constant load ratio R= 0.1. Fatigue tests were stopped either because a frequency drop of 1 Hz, corresponding in most cases to the total specimen failure (broken into 2 parts), or when a number of 5×10^6 cycles was reached.

3. Results and discussions

3.1. S-N curves

The S-N curves corresponding to punched and polished specimens are illustrated in Figure 2. For confidentiality reasons, all the S-N curves are plotted with maximum stress values normalized by the fatigue strength determined for punched specimens at room temperature for R=0.1.

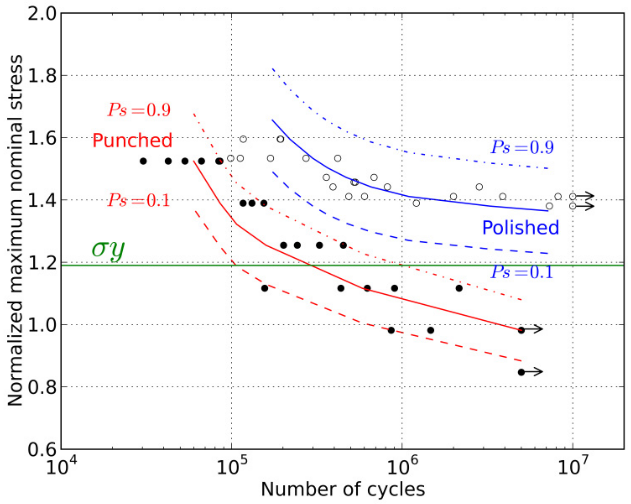

Figure 2 : S-N curves for punched and polished specimens at room temperature for a loading ratio R=0.1

Compared to polished specimens, the median fatigue strength at 5×10^6 cycles for punched specimens shows a drop of about 30%. At higher stress levels, the difference between punched and polished specimens reduces, as fatigue crack initiation is more and more governed by macroscopic plasticity.

3.2. Fractographic observations

To investigate the causes of the fatigue strength drop, SEM observations of the fracture surfaces were done on both punched and polished specimens. On all the observed specimens, crack initiation always occurs on the edge. For punched specimens, it occurs on a punch defect located in the fracture zone. However, for polished specimens, initiation is inter-granular (Figure 3). Since the initiation mechanism depends on the nature of the edge, the effect of the process on fatigue crack initiation is clear. Additional investigations were done on the edge of punched specimens.

3.3. Micro-hardness measurements

Micro-hardness measurements were done starting from the punched edge. The first indentation was 50 µm far from the edge surface and indentations were spaced with 75 µm to avoid measurement interferences. Micro-hardness profile shows a maximum located near the edge, then values decrease and stabilized at a distance of about 200 µm. This depth is representative to the zone mechanically affected by the punching process.

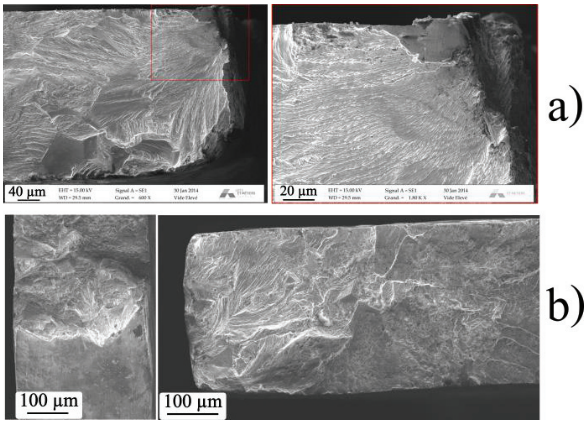

Figure 3 : SEM observations of the fracture surfaces a) punched specimen, b) polished edge specimen

3.4. Residual stress analysis

Longitudinal residual stress induced by the punching process along the rolling direction on specimens edges were estimated using X-Ray diffraction techniques. Due to the low sheet thickness and to the large grain size, analyses have been performed on a stack of 10 sheets. Each stress value was estimated on an irradiated zone of 5 mm². Residual stress values have been determined first on the punched edge surface, then on surfaces obtained after successive layer removal using electrochemical polishing technique.

The profile presents high tensile residual stresses with a maximum located 50 µm below the surface, then stress values decrease when increasing depth (Figure 4-a). The Full Width at Half Maximum (FWHM) of the diffraction peaks is plotted in Figure 4-b. FWHM values decrease and stabilize for a depth of 200 µm. As a consequence, the affected zone is about 200 µm deep. This value is consistent with the depth of the hardened layer determined by micro-hardness measurements.

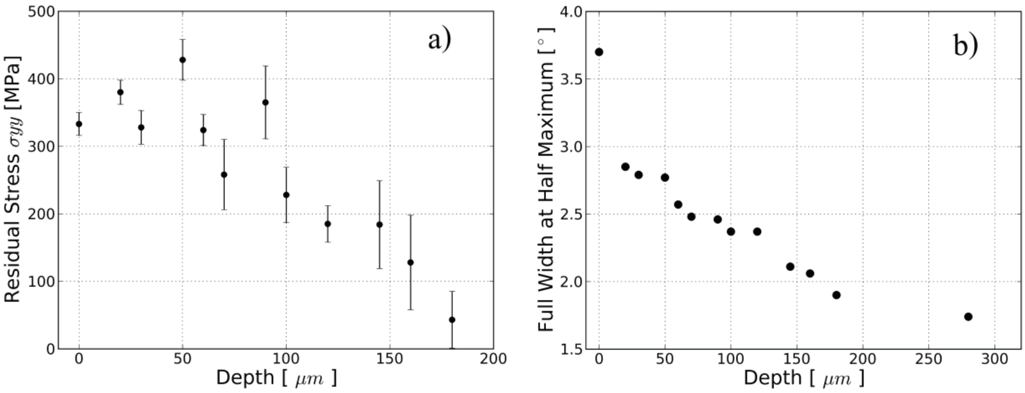

Figure 4 : (a) Longitudinal residual stress σ_{yy} on the edge along depth, (b) Full Width at Half Maximum associated with X-ray analysis

3.5. 3D surface topography

Three dimensional surface topography analyses were performed on the parallel edge zone of some specimens before fatigue testing. The sampling resolution on the edge surface is 0.89 µm along the Y and Z directions and 10 nm along the X direction (see Figure 1-b for annotations). After failure, scan data allows to identify the critical fatigue crack initiation defect (Figure 5-a) and its real geometry. It also allows determining the Murakami [7] parameter (the square root of the hatched area in Figure 5-b). Kitagawa diagram is plotted using the Murakami criterion in Figure 6. Material properties in terms of hardness and residual stresses close and far from the punched edge are used when plotting thresholds. The different combinations of hardness and load ratio are given in Table 2. The 0.55 local value for the loading ratio includes the high tensile longitudinal residual stress on the edge. Murakami criterion is given by approximation (1).

Table 2 : Different combinations used for plotting Murakami criterion

Combination	1	2	3
HV	Mean	Mean	Max
R	0.1	0.55	0.55

$$\sigma_D = \frac{A(HV+120)}{\sqrt{area}^{1/6}} \times \left(\frac{1-R}{2}\right)^{\alpha} \tag{1}$$

with σ_D : median fatigue strength at 5×10^6 cycles, R : loading ratio, A = 1.43 for surface flaws, HV : material hardness, $\sqrt{\text{area}}$: square root of the projected area of a flaw on the plane experiencing the maximum normal stress and α : mean stress sensitivity factor defined by (2).

$$\alpha = 0.226 + HV \times 10^{-4} \tag{2}$$

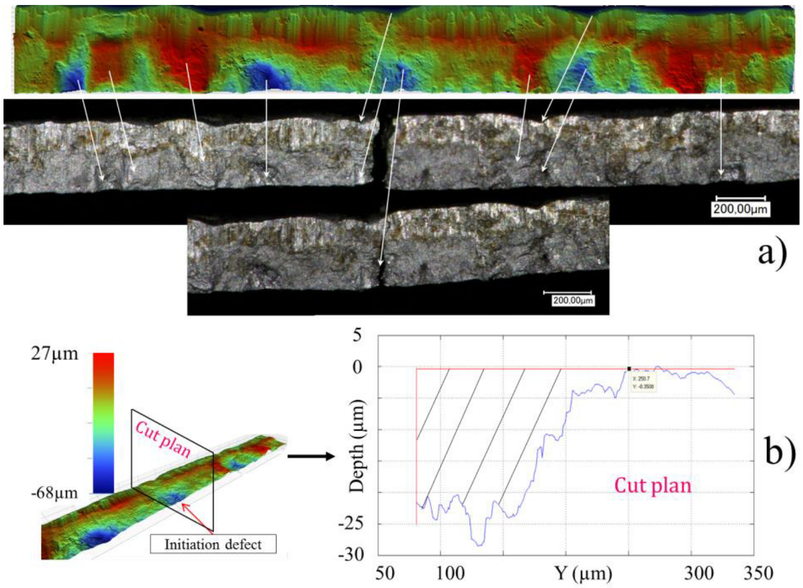

Figure 5 : Fatigue crack initiation defect identification

According to the Murakami criterion previsions, defects with a flaw size less than 60 µm, 20 µm and 90 µm respectively should not affect the fatigue strength, but this assumption is challenged by the fatigue strength drop observed experimentally for punched specimens with typical flaw sizes ranging between 50 µm and 80 µm. As a consequence, Murakami criterion is not perfectly suitable since the material around the defect is affected by the punching process. The better trend of the experimental results is given when only the effect of residual stresses is taken into account (combination 2). Since the Murakami criterion does not provide correct results, the Crossland fatigue criterion has been evaluated to try accounting for the local stress state around defects. It was plotted for punched and polished specimens using the median fatigue strengths obtained for 0.1 and 0.5 load ratios (Figure 6-b). To obtain the local stress concentration factor induced by the defects, Finite Element Analysis have been performed using (first) elastic constitutive model on idealized defects geometries. Local elastic stresses for 3 defects geometries have then been calculated. Results show that Crossland criterion is not adapted for safe fatigue design: the assessed fatigue strength is overestimated (Figure 9). Elastic-plastic FEA have to be carried out in future work together with the use of a non-local high cycle fatigue criterion [8, 9].

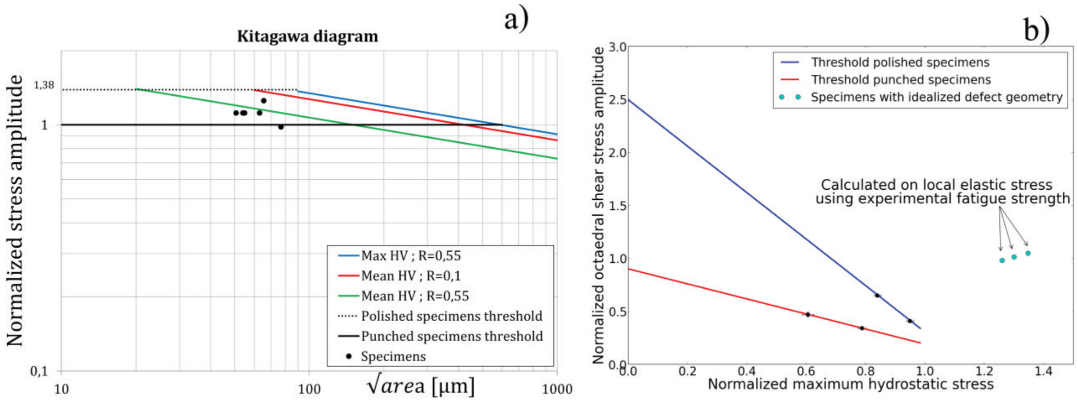

Figure 6 : (a) Kitagawa diagram of punched and polished specimens, (b) Crossland criterion for Fe-Si steel sheets for punched and polished specimens

4. Conclusions and prospects

In this paper, the effect of the punching process on the high cycle fatigue behaviour of thin Fe-Si steel sheets has been investigated. Fatigue tests results on punched and polished edges specimens show a significant drop in the median fatigue strength for punched specimens compared to polished ones. Different factors explain the degradation of the fatigue resistance. According to SEM observations and surface topography, initiation often occurs on a defect localized in the fracture zone of the edge. XRD analyses show high tensile residual stresses induced by the punching process locally on the edge. Micro-hardness measurements near the cut edge exhibit the depth of the mechanically affected zone by the process, which is around 200 µm. The better trend of the experimental results using Murakami criterion is obtained when only local residual stresses are considered. Finally, Crossland criterion gives no safe fatigue strength assessment using elastic constitutive model.

To better take into account the effect of defects on the high cycle fatigue behavior of thin Fe-Si steel sheets, elastic-plastic constitutive model should be used for FEA, and a non-local fatigue criterion [8, 9] should be evaluated.

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